OBSTACLE DETECTION AND AVOIDANCE USING BLAZED ARRAY FORWARD LOOK SONAR

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Award # N0001406WR20060

OBJECTIVES

The long term goal of this project is to increase the level of autonomy in AUVs as they are being used for more complex missions than mine countermeasures. Part of this increase in autonomy will rely on obstacle detection and avoidance and will require a forward looking sonar (FLS) suitable for small vehicles. In the past year, the NPS Center for AUV Research has mounted a University of Washington Applied Physics Lab (UW:APL) Blazed Array Forward Looking Sonar (FLS) on the NPS ARIES AUV and has conducted several data collection tests in Monterey Bay. The goal of the project is to develop Obstacle Avoidance(OA) algorithms for small AUVs using image analysis in a dynamic real time system for detection and avoidance.

APPROACH

The approach is both theoretical and experimental. Theoretical methodology is derived from Artificial Potential Functions which, when globally minimized, provide guidance paths for AUVs that both track the waypoints of the mission but avoid objects in the way. The methodology is useful for both horizontal and vertical plane avoidance. This is tied with real time image analysis, bottom feature extraction, and networked commands to the vehicle guidance and control system. The system is being implemented in the REMUS vehicle as well as the ARIES vehicle at NPS. Follow on work is being conducted for the Feature Based Navigation project at NPS, reported separately.

Figure 1. ARIES Underway with Blazed Array FLS in Nose, Keyport, June 2005

RESULTS

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Obstacle Detection and Avoidance Using Blazed Array Forward Look Sonar**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Center for Autonomous Underwater Vehicle Research,Monterey,CA,93943**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

During FY 2005, NPS installed a two array FLS set from Blueview Technologies, Inc. into the nose cone of the ARIES AUV. Our participation in the AUV Fest 2005 exercise in Keyport, WA. has been reported in [1], and more details as to the analysis of images obtained from the Blazed Arrays are given in the paper presented at Oceans 2005 [2]. During 2006, the theoretical and modeling background using (Artificial Potential Functions) APF, has been developed further and is the subject of the book chapter [3]. Also, the subject of a major presentation and paper given at the Maneuvering and Control of Marine Craft conference in Lisbon, September 2006 gave further details with the complete development from APF Guidance to the details of Blazed Array image analysis and control for the ARIES vehicle, [4].

APF Guidance Theory

Given a total Global Potential Field,

$$V(X,Y,Z,\alpha)>0,$$

composed of track following potentials and obstacle avoidance potentials, with parameters, α, set according to vehicle motion constraints of curvature, the vehicle desired path in a global Navigational Frame, X,Y,Z, evolves according to

$$\dot{x} = f(u), \quad x = [X, Y, Z]^T$$
$$u = [\psi_{com}, \theta_{com}]$$

so that the projection

$$\nabla \boldsymbol{V}.\boldsymbol{f} < 0 \; \forall \; t > 0$$

In developing potential functions for path tracking and obstacle avoidance, it is assumed that functions will be used such that there is a unique local minimum in the region of interest, and that the gradient, $\|\nabla \boldsymbol{V}\| \neq 0$ anywhere.

The path generation model is

$$\dot{X} = U\, cos(\psi_{com})$$
$$\dot{Y} = U\, sin(\psi_{com})$$
$$\dot{Z} = -U\theta_{com}$$

Where, *U* is the forward speed of the vehicle.

The reduction of the potential, *V*, is accomplished using

$$f = -\begin{bmatrix} \eta_1 & 0 & 0 \\ 0 & \eta_2 & 0 \\ 0 & 0 & \eta_3 \end{bmatrix} \nabla \boldsymbol{V}$$

From which $\dot{V} = -\nabla \boldsymbol{V}^T \begin{bmatrix} \eta_1 & 0 & 0 \\ 0 & \eta_2 & 0 \\ 0 & 0 & \eta_3 \end{bmatrix} \nabla \boldsymbol{V} < 0 \quad \forall \ t > 0$

and the η_i are disposable positive parameters to give some degree of adjustment in the resulting path.

The path is generated as the evolution of [*X(t), Y(t), Z(t)*] subject to initial conditions taken from the vehicle's current position at $t = t_0$.

Decoupling the path generation into horizontal and vertical planes, we get

Horizontal Path Generation:

$$\begin{bmatrix} U\cos(\psi_{com}) \\ U\sin(\psi_{com}) \end{bmatrix} = -\begin{bmatrix} \eta_1 & 0 \\ 0 & \eta_2 \end{bmatrix} \begin{bmatrix} V_X' \\ V_Y' \end{bmatrix}$$

Leading to a solution for the heading command. Using, $\eta = \dfrac{\eta_2}{\eta_1}$,

$$\psi_{com} = a\tan(-V_Y', -\eta V_X')$$

Vertical Plane

Considering the vertical plane separately, the solution for the path pitch angle becomes,

$$-U\theta_{com} = V_Z'$$

Potential Function Selection

A UUV mission will be defined in terms of a series of waypoints with nominally straight line segments, and conditions for transition from one to the next. To follow a track defined by 2 waypoints, *i+1* and *i*, we define a track heading,

$$\psi_{track} = a\tan((Y_{i+1} - Y_i),(X_{i+1} - X_i))$$

and define along track and cross track potentials, V_a and V_c

$$V_a = (1 - \beta s); \quad V_c = k_1 e^2; V_z = k_2 z^2$$

where *s* is the along track distance, the cross track error is, *e*, and *z*, the vertical deviation from the nominal altitude /depth command. The track following gradients of potentials are incorporated into the total Global Potential Field gradient by the 3*3 rotation matrix, $\boldsymbol{T}(\psi_{track})$,

$$\boldsymbol{V}'_{track} = \boldsymbol{T}(\psi_{track})[V_a'; V'_c; V'_z]$$

These potentials alone will drive the vehicle through a set of way points provided suitable logic is included for track termination (see Healey, 2006).

Avoidance when objects are detected at locations, [x_j , y_j , z_j], is accomplished through addition of the Gaussian potentials, ***Voj***

$Voj = \sum_{i=1}^{N} V_i\, exp[((X - x_i)^2 + (Y - y_i)^2)/2\sigma_i^2]$ for the horizontal plane avoidance and

$Voj = \sum_{i=1}^{N} V_i\, exp[((X - x_i)^2 + (Z - zo_i)^2)/2\sigma_i^2]$ for vertical plane avoidance and zo is a depth for the object to be avoided. Gradients of the avoidance potentials are added to the track following gradients for the total potential field gradient computation.

The total gradient in the X and Y and Z directions are then

$$V_X' = \sum V_{ojX}' + V_{trackX}'$$
$$V_Y' = \sum V_{ojY}' + V_{trackY}'$$
$$V_Z' = \sum V_{ojZ}' + V_{trackZ}'$$

Path Following

Path Following responses of the REMUS vehicle are simulated and described more fully in [1].

Blazed Array FLS, Object Detection

The Blazed Array Forward looking Sonar FLS can be configured either in the horizontal or vertical planes. In the vertical plane, it is suitable for detecting sudden rises in sea bottoms that would otherwise cause the vehicle to ground while performing mine hinting missions close to the seabed.

The obstacle detection part is a critical part of the control system and first begins with image gathering and analysis.

Figure 2 illustrates the nominal projection of sound fro m the arrays with the vertical mounting. Using a normal to the vertical surface of the stave as a reference, the high frequencies emanate outward at approximately 22.5 degrees and the low frequencies at 45 degrees. Each stave also has approximately 12 degrees of horizontal aperture .

Figure 3 is an example of two images from Blazed Array mounted on the NPS ARIES. The sonar transducer attached to the ARIES AUV is located at the top left corner of each image. The strong linear return in each of the images is typical of an ocean floor without

obstacles. The volume above the ocean floor is the ensonified portion of the water column and is bounded by the upper and lower frequency of each sonar stave.

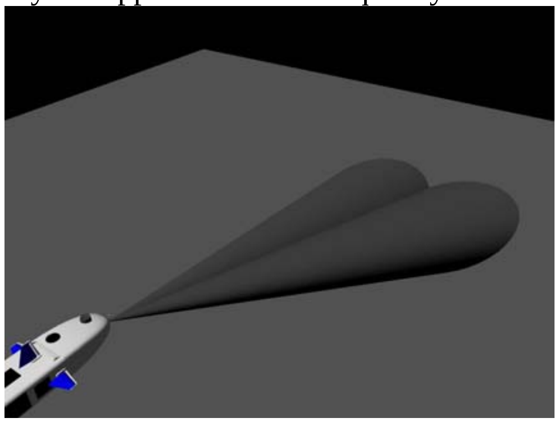


Figure 2. Projection of the Blazed Array Sonar on the Seabed Vertical Configuration

For our application, the sonar is set to a medium low resolution which results in an image size 491x 198 pixels or an effective range of approximately 80 meters. This resolution permits a 1 Hz sonar update rate which is reasonable for obstacle detection for avoidance..

Relating to Figure 3, d_1 and d_2 represent the distance calculations from the nearest and farthest sonar beams (respectively) as they reflect off a featureless ocean floor. Θ_T is the total angle measurement taking into account the sonar mounting angle (Θ_a) and the pitch of ARIES at time t, ($\Theta(t)$).

$$d_1 = h\,tan(\Theta_T)$$
$$d_2 = h\,tan(\Theta_T + 22.5)$$
$$\Theta_T = 45 + \Theta_a + \Theta(t)$$

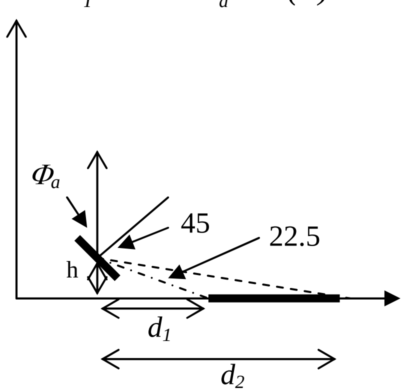


Figure 3 Geometry of Image and Seabottom Ensonification

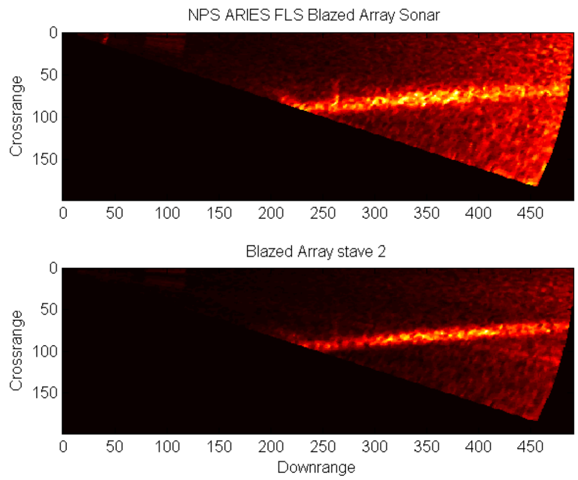
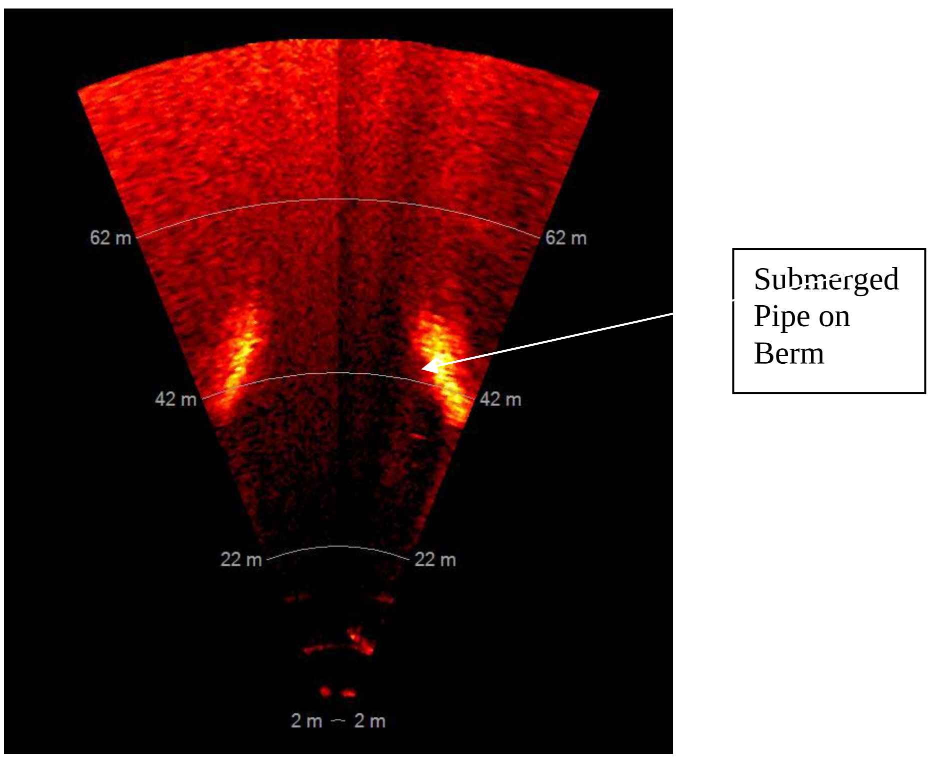


Figure 4. Vertical Configuration for Arrays Showing Strong Returns from Flat Seabed.

Image returns from a submerged pipeline are shown below.



The large strong returns above, indicate that at 40 meters out, a 6 meter high object lies in front of the vehicle and an avoidance maneuver is required. The vehicle smooth avoidance response is clearly shown in Figure 5 below.

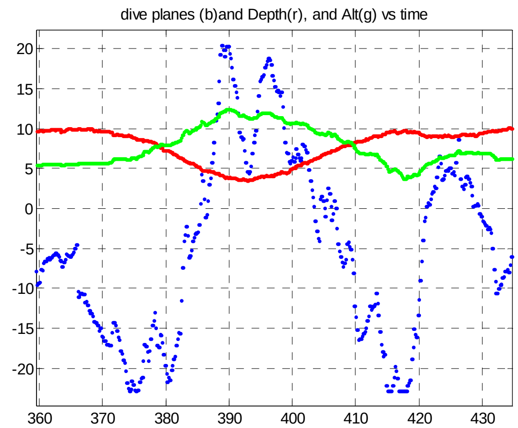


Figure 5 Vehicle Response to Submerged Pipeline, Monterey Bay, June, 2006

Hardware And Software Architecture

A principle feature of the ARIES AUV is its flexibility for housing new hardware and software for testing new methodologies in underwater robotics. There are three components of the Blazed Array sonar: The arrays, the electronics and a PC-104 computer for image storage and processing. The original bow design was modified to mount the arrays. To maintain hydrodynamic efficiency, flexible polyurethane nose was constructed to house the arrays. This minimizes signal attenuation and provides a degree of protection. The construction of the nose permits the arrays to be oriented either in the horizontal or vertical position.

The power and control signals are passed through a water tight bulkhead and attached to the electronics. From there, images are saved and processed using a Windows based PC-104 computer.

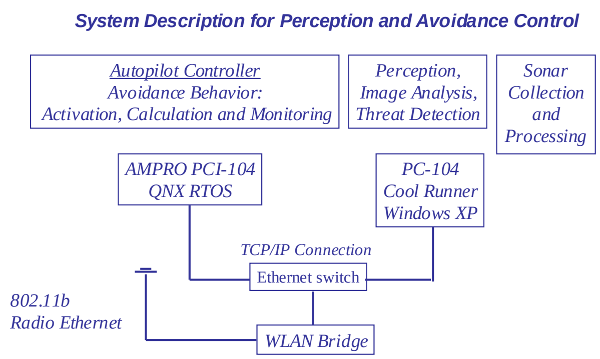


Figure 6 .Hardware / Software Diagram for FLS Obstacle Detection and Avoidance. Mounted in ARIES June 2006

TRANSITIONS

Capability being transitioned into the REMUS vehicle.

RELATED PROJECTS

Tactical Decision Aids (High Bandwidth Links Using Autonomous Vehicles)

PUBLICATIONS

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[2] Horner, D. P., Healey, A. J., "AUV Experiments in Obstacle Avoidance", *Proceedings of IEEE Oceans Conference, 2005* http://web.nps.navy.mil/healey/papers/Oceans2005.pdf

[3] Healey, A. J., Horner, D. P., "Collaborative Vehicles in Future Naval Missions, Obstacle Detection and Avoidance ", Keynote Paper, Proceedings of the IFAC Conference on Maeuvering and Control of Marine Craft, MCMC, 2006, Lisbon, Portugal, September 20-23, 2006 http://web.nps.navy.mil/~me/healey/papers/MCMC06.pdf

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[5] Healey, A. J., "Obstacle Avoidance While Bottom Following for the REMUS Autonomous Underwater Vehicle" Proceedings of the IFAC-IAV 2004 Conference, Lisbon, Portugal, July 5-7, 2004. http://web.nps.navy.mil/~me/healey/papers/IAV2004.pdf

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